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SUBMERGED ARC WELDING OF TITANIUM.(U)
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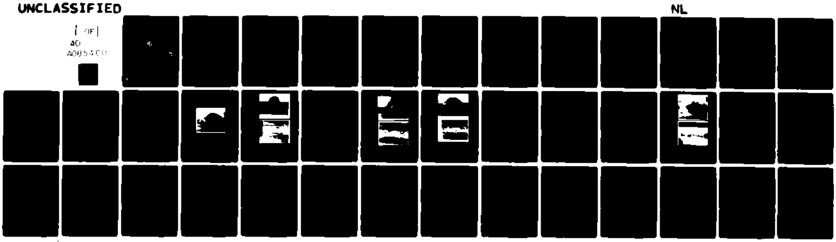

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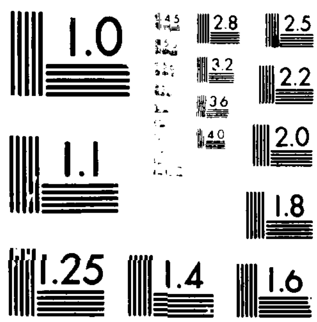

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SUBMERGED ARC WELDING OF TITANIUM

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ABSTRACT

Studies of flux shielded welding of titanium indicate that acceptable submerged arc weld bead shape may not be attained with pure CaF_2 flux. Addition of chlorides to the CaF_2 flux improves the weld bead shape but reduces the deoxidizing potential of the flux. Use of cored electrodes containing chloride salts produces the most acceptable weld bead profiles. Preliminary studies of titanium weld penetration in the presence of several fluoride salts indicate that changes in flux chemistry may be useful in modifying the weld bead profile.

Economic analysis indicates that SAW of titanium can only be competitive with gas metal arc welding if the flux cost can be reduced significantly. A possible method of reducing flux cost may be recycling of the fused slag.

CONTENTS

I. Introduction

Welding of heavy section titanium structures in the open atmosphere presents numerous difficulties, primary of which is prevention of oxygen and nitrogen contamination of the weld metal. In order to prevent such contamination, copious amounts of argon or helium gas, combined with elaborate shields, are used. These arrangements are capable of reducing the total contamination level to an increase of less than 100 ppm oxygen and 20 ppm nitrogen; however, the shields are cumbersome and the initial joint preparation must be closely controlled to provide adequate cleanliness. If any errors are made during the process, the system is unforgiving; and the contaminated weld, if found, can only be corrected by removal and rewelding. All of the above requirements lead to increased fabrication costs for heavy titanium structures.

It has been found that welding of titanium in the presence of a metal halide flux (e.g. CaF_2) has the advantage of providing chemical control of the oxygen content of the weld metal.[1,2] Such control would make the welding process more forgiving of operator error and hence might be expected to simplify and reduce the costs of titanium structural fabrication. Nonetheless, the use of fluxes when welding titanium presents several additional difficulties; viz.:

1. The fluxes are often hygroscopic and must not be stored in the open atmosphere.

2. The pure CaF_2 flux produces welding arc instabilities, a somewhat rough weld bead surface and an unacceptably high weld bead contact angle.

3. In order to control weld metal oxygen content, the fluxes must be of high purity. The purity requirement increases the cost of the flux substantially.

In accordance with these difficulties, the previous year's effort has been devoted to studying:

1. Use of flux cored electrodes as a means of reducing moisture contamination of the flux,

2. Methods of improving weld surface smoothness and weld bead contact angle, and

3. Economic comparison of existing titanium gas-metal arc welding (GMAW) technology with possible submerged arc welding (SAW) technology.

Partial success has been achieved in each of the first two areas, while the economic analysis indicates that SAW can compete with GMAW only if the flux costs can be reduced significantly. Possibilities for flux cost reduction are outlined.

In addition, a preliminary study of the effects of several metal fluorides on weld penetration has been made. The results suggest that variation of titanium weld flux chemistry may provide a means of controlling weld bead shape and arc melting efficiency.

II. Materials

All submerged arc welds were made on 19 mm (0.75 inch) Ti-6Al-4V ELI (extra-low interstitial) plate received from RMI Titanium Company of Niles, Ohio. The solid welding electrodes were also Ti-6Al-4V, purchased in three diameters from Astro Metallurgical Corporation of Wooster, Ohio. The mill certifications of these materials are given in Table 1.

Flux cored welding electrodes were fabricated from 3.2 mm diameter Ti-3Al-2.5V tubing with wall thicknesses of 0.4 mm and 0.8 mm. The flux, ground to a fine powder, was tamped into the tube with a long rod. Sections of electrode approximately six feet long could be made in this manner, which was sufficient to form one weld bead. Attempts to fabricate longer sections of electrode by swaging 6.4 mm or 9.6 mm diameter tubing, failed due to early cracking of the alloy tube walls. It has been reported that swaging may be successful if the tubing is pure titanium rather than an alloy.[3]

Optical purity CaF_2 was the primary flux used throughout this investigation. Lump crystals were obtained from Optovac, Inc. of North Brookfield, Massachusetts. Additions of KCl and NaCl were also used. The KCl crystals were of optical quality, again produced by Optovac. The NaCl crystals were reagent grade, obtained from Baker Chemical

Company. The use of reagent grade NaCl in place of optical grade was justified on the decreased hygroscopicity of NaCl compared to KCl.

The fluoride fluxes used in the gas-tungsten arc (GTA) penetration study were reagent quality powders. No attempt was made to dehydrate each of these powders as studies of weld metal chemistry were not to be made. Care was taken to ensure that each powder remained as dry as possible. This was practical in every case except KF which was found to be deliquescent and had to be eliminated from the series.

Table 1. Starting Materials,
Base Metal and Electrodes

Base Metal

Ingot Analysis No. 803175

	C	Fe	Al	V	N	O	H	Ti
Certified	.02	.17	6.1	3.8	.012	.117	.010	bal.
Check 1	---	---	---	---	.0088	.100	---	---
Check 2	---	---	---	---	.0121	.176	---	---

Annealed 1/2 hour, 927°C, A.C. + 1 hour, 760°C, A.C.

Mechanical Properties

	Yield Strength MPa (ksi)	Tensile Strength MPa (ksi)	Elongation %
Longitudinal	863 (125)	934 (135)	13.5
Transverse	925 (134)	993 (144)	12.5

Welding Electrodes

Diameter, mm (in)	C	Fe	Al	V	N	O	H	Ti
3.2 (.125)	.019	.15	6.28	4.11	.006	.078	.002	bal.
Check 2	---	---	---	---	.010	.180	---	---
2.4 (.093)	.019	.15	6.28	4.11	.008	.078	.002	---
Check 2	---	---	---	---	.010	.180	---	---
1.6 (.062)	.019	.15	6.28	4.11	.008	.078	.009	---

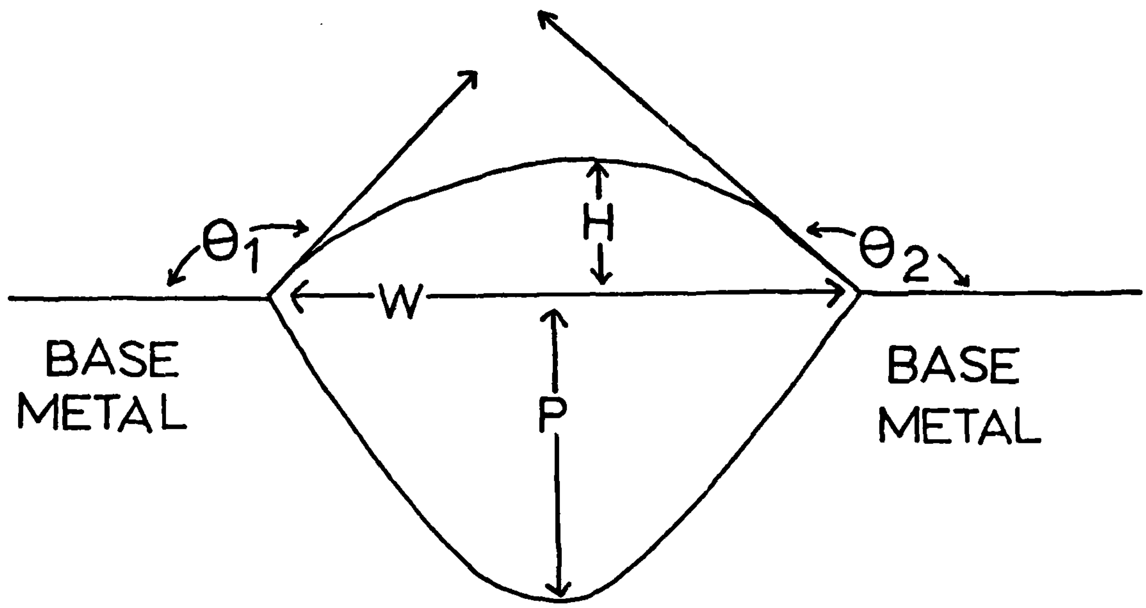
III. Submerged Arc Weld Bead Appearance

As noted in the introduction, pure CaF_2 flux has beneficial effects on titanium weld metal oxygen content, but produces unacceptably poor weld beads, primarily in terms of weld bead contact angle. Since the bead appearance observed with pure CaF_2 would preclude use of titanium SAW without further improvement, a study was made of the effects of process parameters and flux chemistry on weld bead appearance.

1. Parametric Study

Initially, the effects of weld voltage, current, and electrode diameter were evaluated in a 2^3 factorial experiment. The weld travel speed was held constant at 30 cm/sec. The dependent parameters consisted of arc stability (monitored as described in reference 2), weld metal oxygen content, nitrogen content, weld bead shape, weld metal hardness and bead surface roughness. The contact angle, penetration, bead height and width are defined in Figure 1. The results of this series are shown in Table II.

As can be seen in Table II, the oxygen content of the weld metal is essentially constant due to the refining action of the CaF_2 flux. The nitrogen content varies by a large amount,



H : Bead Height

P : Depth of Penetration

W : Bead Width

Θ : Contact Angle $= (\Theta_1 + \Theta_2)/2$

Figure 1. Parameters used to define weld bead shape.

Table II. Effect of Voltage, Current and Electrode Diameter on SAW Titanium using CaF_2 flux.

Weld	Voltage, volts	Current, amperes	Electrode diameter, mm	% oxygen	% nitrogen	Arc stability	Surface roughness*	Bead width, mm	Bead height, mm	Penetration, mm	Contact angle, degrees	Hardness, Rc
1	30	300	3.2	0.12	0.069	3	S	13	5	2	114.5	43.2
2	30	400	3.2	0.12	0.048	3	S, D	14	4	3	112.5	43.3
3	36	300	3.2	0.099	0.066	1	S	16	5	1	113.5	35
4	36	400	3.2	0.11	0.056	2	S, D	16	6	3	144.5	40.6
5	30	300	2.3	0.11	0.081	3	S, D	11	5	2	105	38.5
6	36	400	2.3	0.10	0.049	2	S	17	5	3	141.5	41.9
7	30	400	2.3	0.11	0.044	3	very S, D	14	8	3	99	39.7
8	36	300	2.3	0.10	0.045	2	S	13	5	1	122	44

Electrode extension - 15 mm
Arc stability rated on 1 - 3 scale with 1 as most stable.

*S = Smooth
D = Discolored

with the contamination increasing as the electrode melting rate decreases. This indicates that much of the nitrogen contamination is due to absorption of atmospheric gases on the hot unshielded electrode as it emerges from the weld torch contact tip. This is consistent with previous studies of nitrogen contamination during titanium SAW.[2] Supplementary argon shielding would be expected to reduce this nitrogen contamination.

The arc stability is increased with higher arc voltage. The bead shape parameters, height, width and penetration generally increase with increased weld heat input, as expected. The results indicate that the weld bead contact angle can vary widely depending upon operating parameters; however, neither welds 4 nor 6, which had more favorable contact angles, were acceptable. The cross section of each revealed lack of fusion between the bead top and the base plate, as shown in Figure 2.

Based upon the above series of tests, weld 3, made using 300 amperes at 36 volts, was chosen as possessing the best set of operating parameters. The cross section of this bead is shown in Figure 3. It should be noted that none of these welds produced a bead which would be acceptable for producing groove welds in thick plate butt joints. Although improvements in bead shape were made by altering the weld process variables, no weld made with pure CaF_2 flux provided a bead shape which would eliminate slag entrapment or lack of fusion defects in multiple pass weldments.

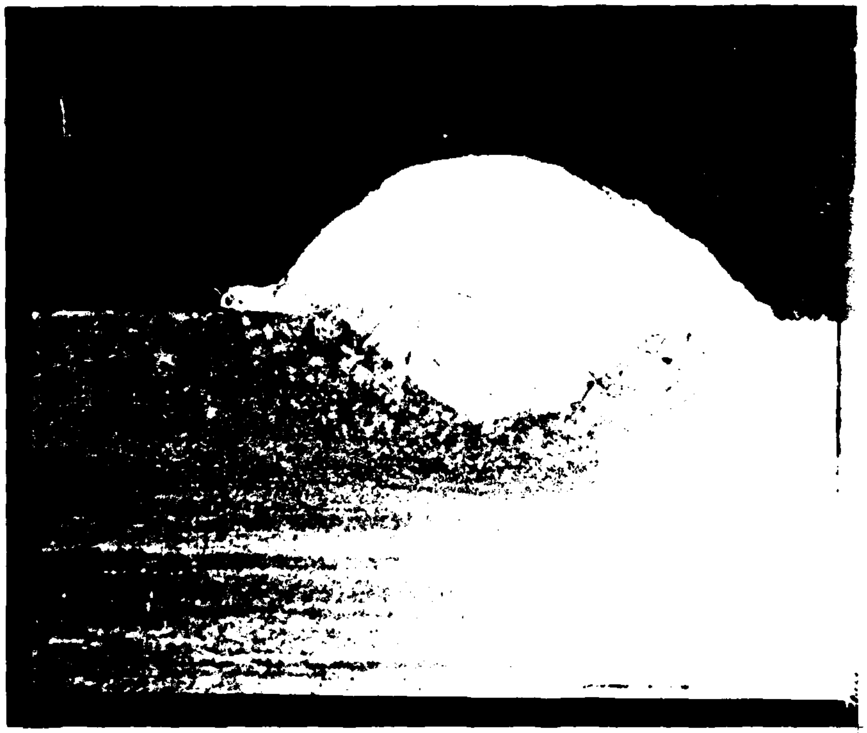
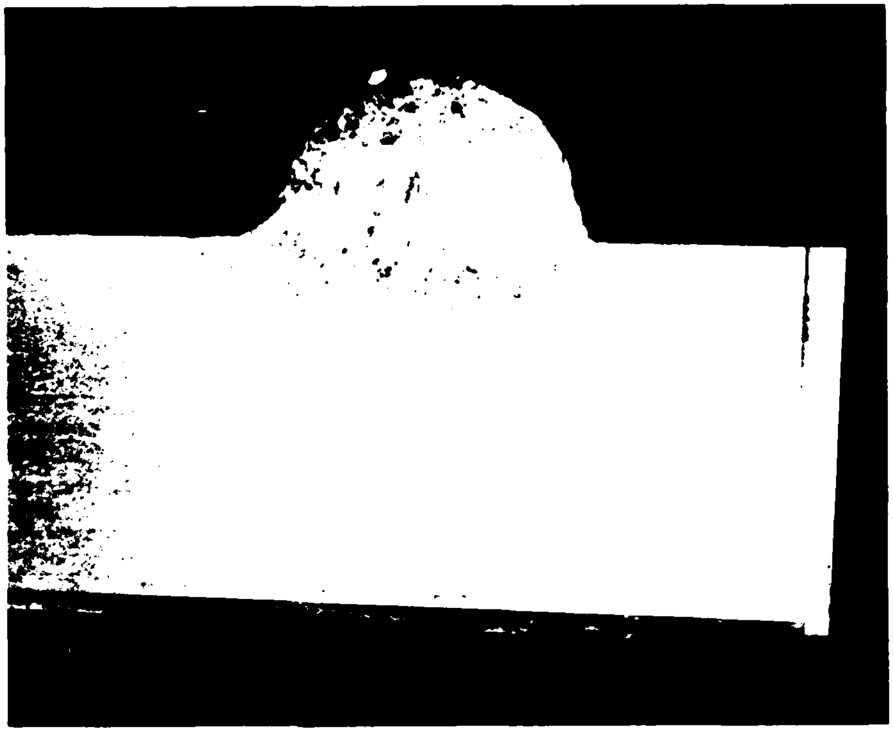


Figure 2. Cross section of weld 6 of Table II. Although this weld possessed a favorable contact angle, the penetration of the bead near the edges was deemed inadequate. This weld is similar in shape to weld 4 of Table II.

A.



B.

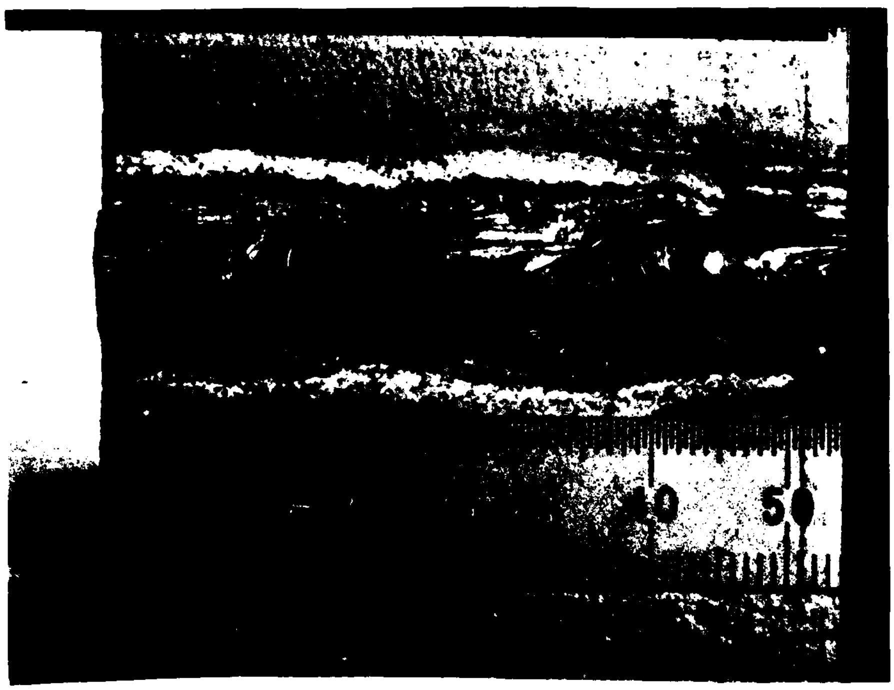


Figure 3. A.) Cross section of weld 3 of Table II.

B.) Surface of same weld.

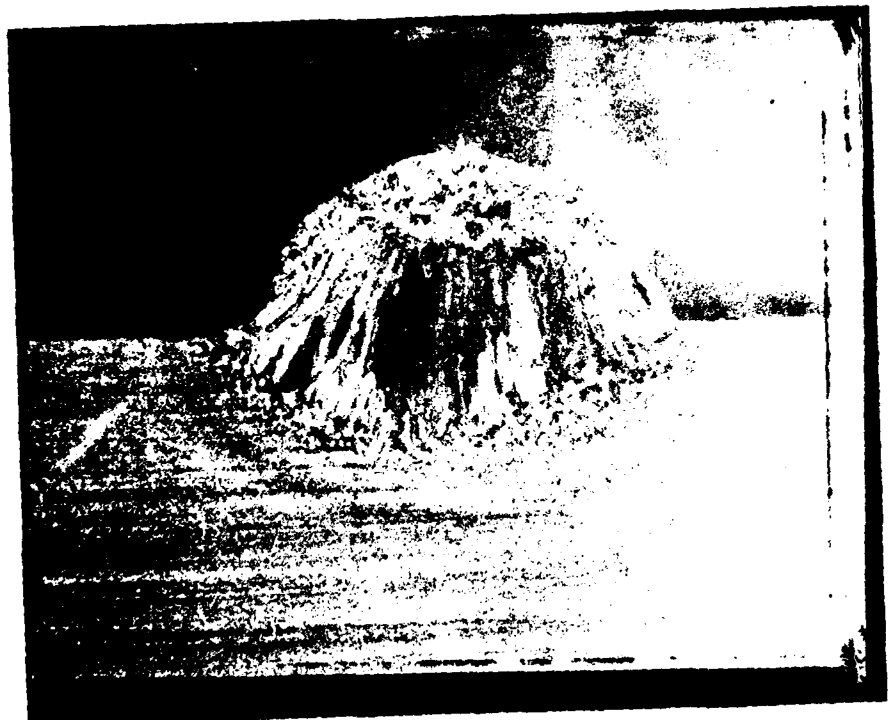
This weld was chosen as the standard from which subsequent improvements in weld bead shape are judged. Note that the height and contact angle of this bead make it impractical for producing multipass groove welds.

Two additional process modifications were examined in hopes of improving the weld bead shape in the presence of pure CaF_2 flux. In the first, the electrode was given a tilt of either $+15^{o}$ (leading) or -15^{o} (trailing). In the second modification, welds were made with 3.2 mm diameter tubes, instead of solid electrodes. The purpose of the latter modification was to test the changes in electrode melting behavior (and bead shape) which might be expected when using an alloy core or flux core electrode. Table III indicates that both of these modifications result in significant changes in the weld bead shape, although neither produced the weld shape which is desired. A leading electrode tilt increases the weld penetration depth but does not have much effect on the bead contact angle. Use of tubular electrodes produces much shallower penetration but improved weld contact angles. Photos of each type of weld are shown in Figures 4 and 5.

2. Flux Chemistry Study

An alternative to process modification of weld bead shape is modification of bead shape by changes in flux chemistry. Investigation of this possibility is of particular interest as Soviet investigators have long stated that addition of chlorides to flouride improves their operating characteristics. If one of these improvements includes bead shape, then use of the very hygroscopic chlorides might well be justified.

A.



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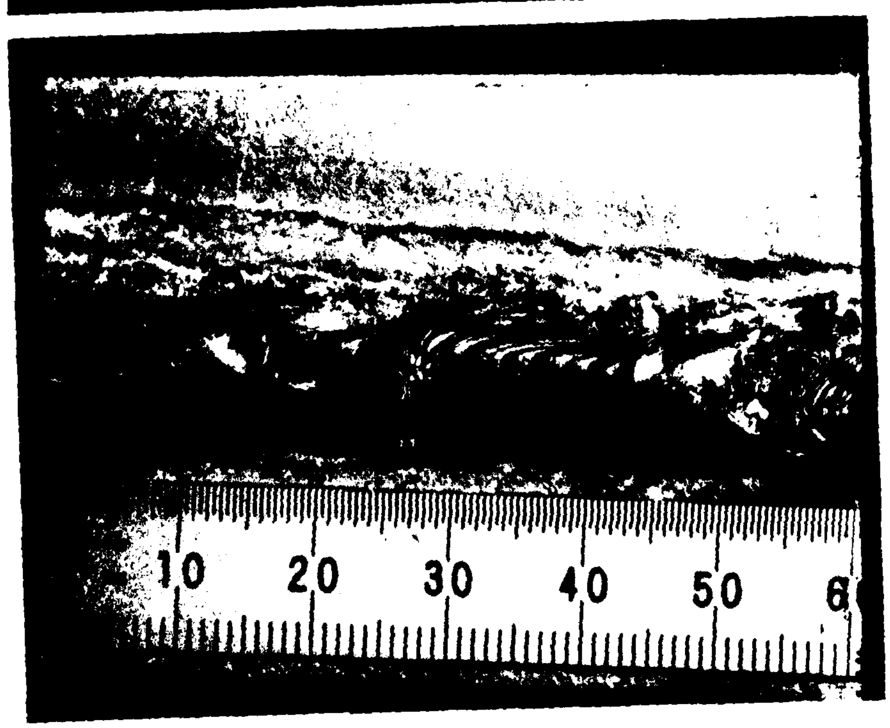


Figure 4. A.) Cross section of weld 9 of Table III, made with +15° (leading) electrode tilt.

B.) Rough weld surface of the same weld. Note that slag is attached to the toe of the weld.

A.

B.

Figure 5.

A) Cross section of weld 11 of Table III, made with tubular electrode. Note the much shallower weld penetration when using tubular electrodes.

B) Surface of same weld bead. The lower contact angle facilitates slag removal at the toe of the weld, although some slag still remains. The surface has more uniform ripples but a more variable width than previous welds.

Table III. Effect of electrode tilt angle and tubular electrodes on weld bead shape when using pure CaF_2 flux.

Weld	Tilt angle	Tube wall, mm	% Oxygen	% Nitrogen	Surface roughness	Bead width, mm	Bead height, mm	Penetration, mm	Contact angle, degrees	Hardness, Rc
9	$+15^{\circ}$	--	0.11	0.075	Rough	13	5	3.5	117.5	38.6
10	-15°	--	0.11	0.074	Smooth	18	6	2.0	113.5	40.8
11	0°	0.4	0.17	0.084	Rough	16	5	1.0	136	--
12	0°	0.8	0.11	0.060	Smooth	10	4.5	0.5	134	--

Each weld, 36V, 300 amperes, 15 mm electrode extension, cm/sec, 3.2 mm diameter electrode

Three methods of adding chlorides to the CaF_2 flux were tested, viz.:

1. Blended additions of NaCl or KCl, i.e. mechanical mixture of the powders,
2. Fused additions of KCl, i.e. co-melting of the salts, and
3. NaCl and KCl flux cored electrodes operating in a pure CaF_2 granular flux.

The latter technique of adding chlorides through a tubular electrode has the distinct advantage of keeping the strongly hygroscopic chloride flux sealed within the cored electrode. If operable, this technique of chloride addition should have significant advantage over the use of blended or fused fluoride-chloride granular fluxes.

The results of the chloride flux tests are shown in Table IV. The effects of the chloride additions are numerous, although certain major trends are apparent.

The oxygen content of the weld metal is elevated compared with pure CaF_2 (cf. Table II). This may be due to slight moisture pick-up due to the chlorides, although a more probable explanation would be that the increased NaCl or KCl content has decreased the thermodynamic activity of the CaF_2. Based upon a Temkin regular solution model, 20 mole percent NaCl or KCl in CaF_2 would decrease the activity of the CaF_2 by 40 to 50%.[4] This could easily account for the reduced deoxidizing

potential of the CaF_2. Use of $CaCl_2$ instead of NaCl or KCl may restore the deoxidizing potential to the flux. Unfortunately, $CaCl_2$ is not preferred due to its high hygroscopicity.

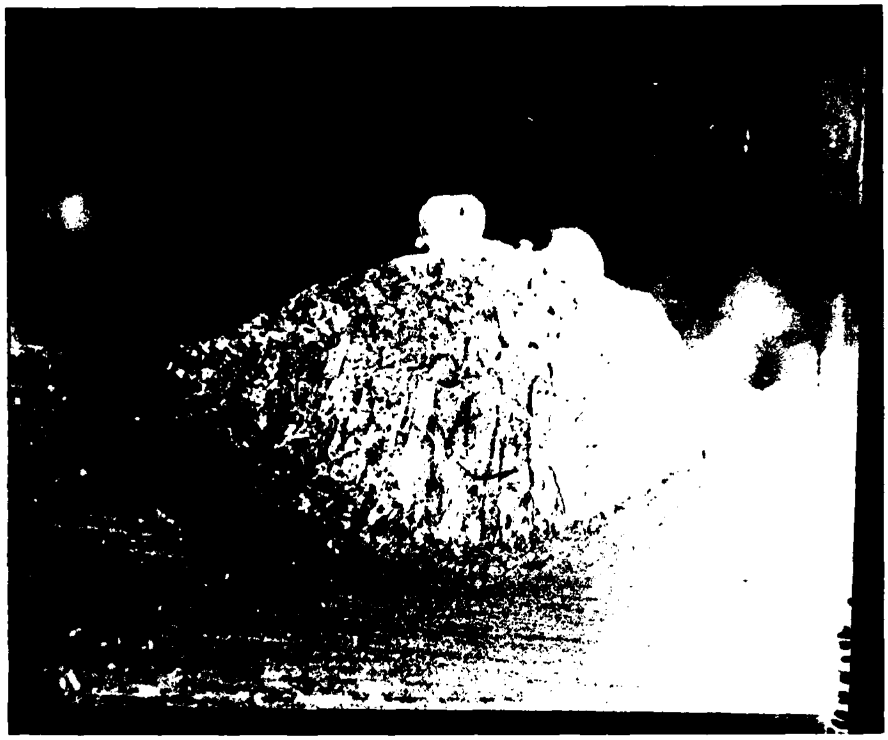
The nitrogen contamination of the weld metal is markedly reduced by the chloride additions. This may be due to the strong fume generation around the electrode caused by the chlorides. This fume surrounds the hot electrode, thus reducing atmospheric absorption. The same reduction in nitrogen contamination may be achieved by external argon shielding of the electrode.[2]

As in the empty tubular electrode welds described in Table III, the flux-core tubular electrode welds generally had elevated oxygen and nitrogen levels. This may be due to enhanced atmospheric absorption on the electrode, which runs hotter at the same electrode extension due to the increased current density. Supplementary argon shielding may reduce this contamination.

The surface roughness of the chloride flux welds was not significantly improved over the pure CaF_2 flux welds. Although the ripples were somewhat more uniform, the chloride fluxes seemed to produce more discoloration and weld spatter than pure CaF_2.

The weld beads are much wider with chloride additions to the flux. This is likely due to the addition of a new type

A.



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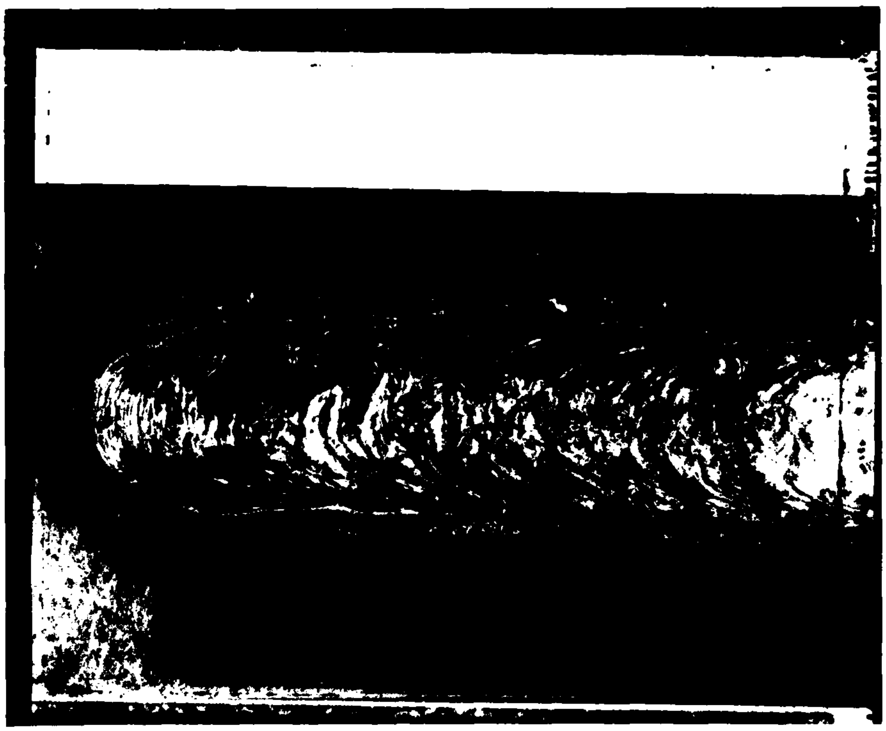

Figure 6.

A) Cross section of weld 24. Note improved contact angle and improved melting efficiency compared with weld 3 shown in Figure 3.

B) Surface of weld 24. Although the contact angle is improved, the surface roughness is worse than a weld made with pure CaF_2 flux.

of negative ion to the arc plasma. The pure CaF_2 flux has only fluorine as a negative ion. Fluorine has the highest affinity for electrons of all elements and can be quite effective in quenching plasmas, i.e. in reducing the electron concentration of the plasma. SF_6 gas is used as an insulator in high voltage equipment for this very reason. Recent Soviet studies show that 2.5% SF_6 in argon constricts a welding plasma by a factor of four.[5] Steel welding fluxes, which are high in CaF_2, have been found to narrow the width of welding arcs. The substitution of chlorides for fluorides in the present case has obviously widened the submerged arc plasma.

The height of the fused region remains approximately the same, although the depth of penetration is greatly enhanced, especially when using tubular electrodes. The greater penetration and weld bead width indicates that chloride additions to the flux greatly enhance the melting efficiency of the process. This is seen in Figure 6, which shows a much larger weld bead compared with Figure 3.

One of the most significant advantages of using chlorides in the flux is an improvement in the weld bead contact angle. Nearly all of the beads made using chloride additions possessed contact angles which would be acceptable for multipass groove welds.

The arc stability of the welds made with chloride fluxes appeared to be similar to welds made with pure CaF_2.

The failure of welds 19 and 20 to follow the common trends found in the other welds of Table IV may be due to loss of chloride upon fusion. Only two melts were fused in the vacuum furnace due to contamination of the system with chloride salts. The flux compositions shown for welds 19 and 20 in Table IV cannot be taken as accurate due to evaporative losses during fusion. It is possible that flux 19 had more chloride than flux 20. In any case, the fused fluxes were not found to behave differently than the blended fluxes in terms of the parameters studied here. A more complete evaluation of fused chloride-flouride fluxes is needed in order to determine if fused fluxes are preferable to blended fluxes.

3. Conclusions

The weld bead shape may be modified by the choice of weld process parameters, although no bead made with pure CaF_2 flux could be expected to produce defect-free groove welds. The addition of chlorides to the flux improves the bead shape and melting efficiency but has a detrimental effect on the surface roughness and oxygen content of the weld metal. Groove welds of acceptable shape can be made with chloride containing fluxes. Fume generation during SAW with chloride containing fluxes is excessive and should receive further study. Flux cored welding electrodes produced the least amount of welding fume.

Table IV. Effects of chloride additions and mode of addition to CaF_2 titanium SAW fluxes

Weld	Granular flux	Electrode,	% Oxygen	% Nitrogen	Surface roughness	Bead width, mm	Bead height, mm	Penetration mm	Contact angle, degrees	Hardners, Rc
13	5% NaCl blended	solid	0.11	0.019	rough	17	5	6	133.5	34.6
14	10% NaCl blended	solid	0.14	0.023	rough	15	5	5	141	39.8
15	20% NaCl blended	solid	0.17	0.020	very rough, undercut	17	2	5.5	severely undercut	42.7
16	5% KCl blended	solid	0.16	0.025	rough	15	4	3	137	40.7
17	10% KCl blended	solid	0.15	0.019	rough	19	5	4	138	--
18	20% KCl blended	solid	0.12	0.015	rough, ropy	17	5	4	128.5	39.5
19	5% KCl fused	solid	0.13	0.028	smooth	11.5	4	2.5	135	42.4
20	10% KCl fused	solid	0.10	0.012	smooth	8	5	0.5	109	40.8
21	100% CaF_2	NaCl core 0.8mm wall	0.12	0.033	smooth	16	5	4	115.5	--
22	100% CaF_2	NaCl core 0.4mm wall	0.12	0.017	rough	17	5	3	105	--
23	100% CaF_2	KCl core 0.8mm wall	0.19	0.043	smooth	21	4	3	139	--
24	100% CaF_2	KCl core 0.4mm wall	0.19	0.14	rough	20	4	5	142.5	--

36V, 300 amperes, cm/sec, 15mm electrode extension, 3.2mm diameter electrode

Future improvements to the process might include:

1. Use of pulsed welding power supplies to improve metal transfer and bead surface appearance, and

2. Use of Ca - CaF_2 fluxes with chloride additions. The free Ca which dissolves in CaF_2 may return the deoxidizing capacity of the chloride containing flux to the 1000 ppm level. Initial attempts to make such a flux have been unsuccessful due to inadequate melting facilities, but in principal these fluxes should not be difficult to produce.

IV. Economic Analysis of GMAW vs. SAW of Titanium

The development of a technologically successful method of submerged arc welding titanium will be of little use unless the process is also economical. The technological requirement of high purity starting flux material has shed some doubt as to the ultimate economics of SAW titanium. A flux which costs $18/kg. and is consumed at the rate of 4.5 times the electrode deposition rate (by weight) can add significantly to the fabrication costs. Hence, it was deemed necessary

to investigate the economic impact of SAW titanium compared with the current technology of gas metal arc (GMA) welding.

The economic model was chosen to be as simple as possible yet still differentiate between the relative costs of the two processes. In many cases large scale production costs are not available and may only be estimated. The major variables of concern are electrode cost as a function of electrode diameter, and the bulk price of high purity CaF_2 flux. The analysis shows the total cost to be most sensitive to these two factors, which are also the least well known.

The model assumes that capital costs are similar for both processes and that the processes may be compared based upon the costs of consumables and labor only. The joint geometry of each type of weld is also considered to be constant, although variable joint geometry can easily be handled by the program. The input data included:

1. Electrode feed rate vs. welding current
2. Weld travel speel
3. Weld voltage
4. Electrode price as a function of wire diameter
5. Rate of flux consumption per ampere of welding current
6. Argon use rate

7. Argon cost
8. Labor cost
9. Arc time

The standard conditions for each weld are shown in Table V. Parameters for GMA welding were obtained from Mr. J. Crisci of the Naval Ship Research and Development Laboratory. SAW parameters were developed experimentally. The standard flux cost of $18/kg. was estimated as a reasonable bulk price for reagent quality powder. This figure is substantially less than current market price for optical quality lump CaF_2 in less than 10 kg. lots, but it is not far from the market price of reagent grade CaF_2 powder in 50 kg. lots. It is assumed that the large lot savings would approximately equal the melting and purification costs necessary to refine reagent grade powder.

The results of the comparison based upon the standard welding conditions is shown in Figure 7. It will be noted that shielding and electrode costs dominate the total weld cost. For the GMA process, the single most important cost is the electrode while in SAW the electrode cost and the flux cost are approximately equal. Although the larger diameter electrode used in SAW is somewhat less expensive than the GMAW electrode, the savings in electrode cost is not sufficient to offset the cost of the welding flux. It should be noted that the use of auxiliary argon shielding with the SAW process adds less than one percent to the cost of the submerged arc weld.

Table V. Standard Welding Parameters
Used in the Economic Analysis of Welding Ti-6Al-4V

	GMAW		SAW
Welding current, amperes	350		370
Welding voltage, volts	20		36
Electric power cost, $/KWH	-	0.04	-
Argon cost, $\$/m^3$	-	5.30	-
Electrode diameter, mm	1.6		3.2
Electrode price, $/kg.	77.38		69.77
Travel speed, cm./sec.	0.83		0.67
Labor cost, $/hr.	-	15.0	-
Arc time, min./hr.	30		24
Shielding gas, ℓ/sec.			
A) Torch	0.31		(0.31 optional)
B) Trailing	0.71		-
Plate thickness, cm.	-	5	-

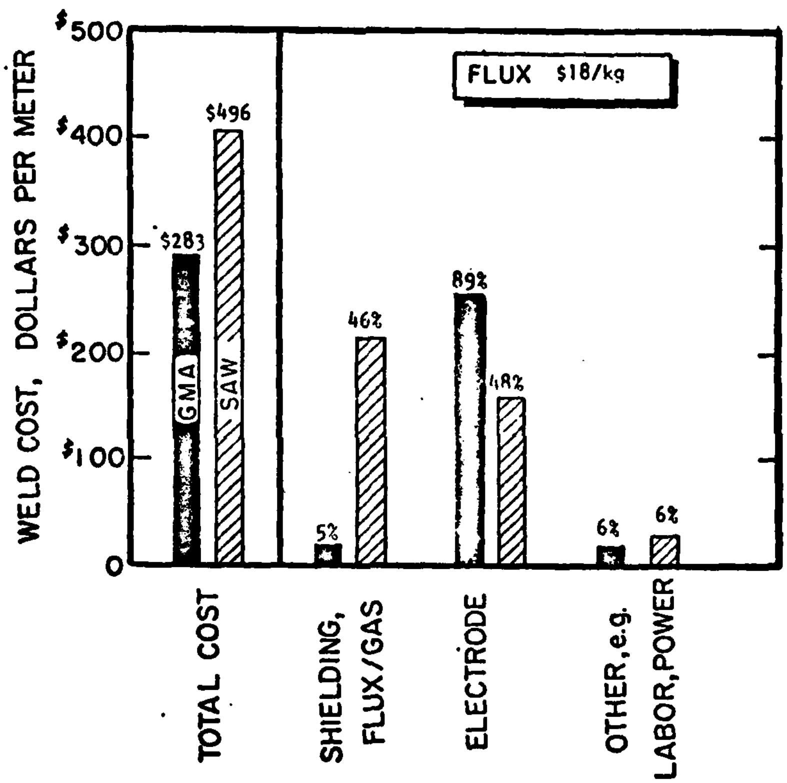

Figure 7 -- Estimated cost of welding 5 cm thick titanium plate by GMA or SAW based upon conditions in Table V.

The above analysis assumed that the titanium flux is discarded for zero scrap value after use. In fact this flux is relatively inert and it may be possible to reuse the flux with only minor reprocessing. If the flux cost could be reduced to $2.25/kg. by multiple use, the SAW process would become competitive with the current GMAW process. (See Figure 8). The crossover where GMAW and SAW are equal in cost occurs at a flux cost of $1.26/kg..

From the foregoing analysis, it is clear that SAW of titanium is very sensitive to flux cost and electrode cost while GMAW is primarily sensitive to electrode cost. Although GMAW uses a smaller diameter electrode, which is slightly more expensive, the sensitivity to electrode costs between the two processes does not differ appreciably. From this analysis it can be seen that the only way in which SAW can compete economically with GMAW is if the flux cost can be reduced significantly. As noted previously, this may be possible through recycling of the flux. Such studies are underway.

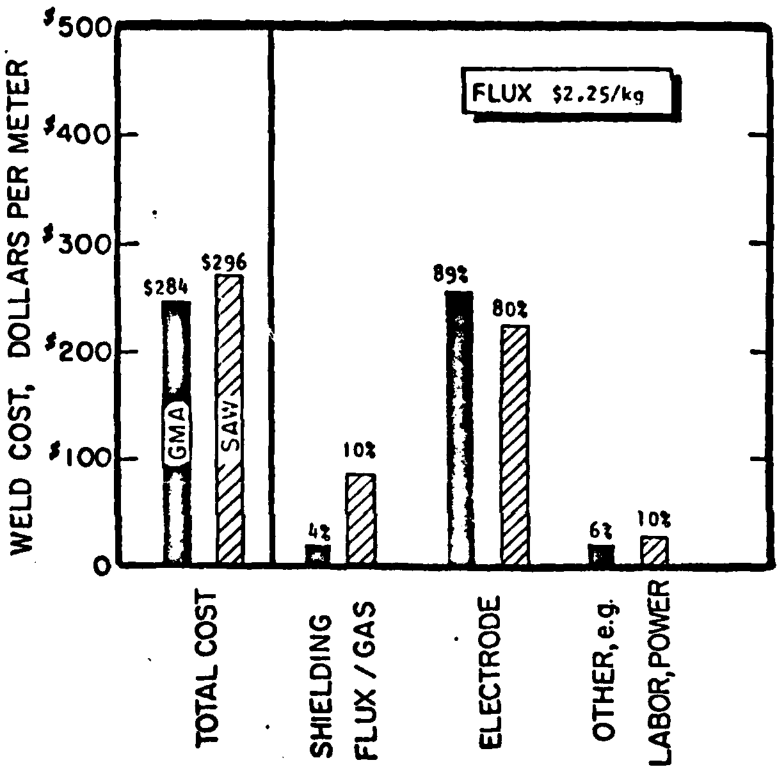

Figure 8 -- Estimated cost of welding 5 cm thick titanium plate by GMA or SAW based upon a flux cost of \$2.25/kg and all other conditions as shown in Table V.

V. GTAW in the Presence of a Fluoride Flux

Soviet investigators have reported a process termed "semi-submerged arc" welding wherein a gas-tungsten arc weld is made in the presence of a thin paste flux.[2] This process was originally applied to titanium weldments but it is reported to be applicable to other metals as well. The flux is generally composed of a mixture of alkali and alkaline earth fluorides. It is reported that the flux changes the efficiency of melting and improves the arc stability. A brief study was performed to verify these reports.

Fine powders of LiF, NaF, RbF, CsF, MgF_2, CaF_2, SrF_2 and BaF_2 were mixed with propanol and spread across the surface of a titanium plate in thicknesses of 0.12, 0.25 and 0.5 mm and GTA welded at 16 volts, 200 amperes, and 25 cm/min., with 0.63 ℓ/sec. Ar shielding gas. The dependent parameters studied included arc length, arc width at the midplane, arc stability and weld shape. The results are shown in Table VI. Although changes in weld pool shape and size are noted, they are not as dramatic as has been claimed by the Soviet investigators. This may be due to the fact that 200 amperes was used in this study, while Soviet studies may have involved much higher welding currents. The effects of changes in plasma jet behavior and weld pool surface tension on weld penetration and

Table VI. Results of GTA Welding of Titanium in the Presence of a Paste Flux

Flux	Flux Thickness, mm	Arc Length, mm	Arc Width, mm	Weld Width, mm	Weld Depth, mm
None	--	28	10	11	2
LiF	.12	26	10	12	<1
	.25	19	9	12	<1
	.50	14	8	11	3
NaF	.12	21	9	5	2
	.25	26	12	7	2
	.50	19	10	6	2
RbF	.12	25	9	10	2
	.25	26	11	8	2
	.50	26	11	6	2
CsF	.12	24	11	8	2
	.25	24	10	9	2
	.50	23	10	8	2
MgF_2	.12	20	10	6	3
	.25	21	10	6	3
	.50	21	10	5	2
CaF_2	.12	27	14	10	2
	.25	27	13	11	2
	.50	26	13	10	2
SrF_2	.12	27	10	9	1
	.25	27	10	9	2
	.50	27	10	9	2
BaF_2	.12	28	11	10	1
	.25	29	12	10	1
	.50	29	12	11	1

shape should be more pronounced at higher welding currents. Further studies at varying current levels are planned, although a welding chamber will be required to contain the fumes as the operator experienced respiratory irritation during this study.

VI. Additional Work

In addition to the studies reported, work has proceeded in two other areas during the past year, viz. construction of a chamber for controlled atmosphere testing by SAW, GMAW and GTAW, and construction of a Cl_2 - HCl gas train for use in drying the hygroscopic chloride fluxes. Although each of these are now operational, no data has yet been generated as a result of their construction. Each is expected to be of importance in studies during the coming year.

VII. Summary

An experimental and economic study of submerged arc welding of titanium has shown the following:

1. Modifications to the welding process can influence the weld bead shape when using pure CaF_2 flux, but the changes are insufficient to provide the control of bead shape which is required for production of groove welds.

2. Modification of the flux chemistry by the addition of chlorides improves the melting efficiency and provides acceptable bead shape, however, the deoxiding potential of the flux is reduced.

3. Economic comparison of GMAW and SAW of titanium indicates that SAW will be economic only if flux recycling is possible.

4. Gas tungsten arc welding in the presence of a fluoride flux does affect the arc behavior and melting efficiency. The extent of the change depends upon the flux composition.

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